This project started as a laboratory experiment entitled **"Laboratory Measurements of Multi-Frequency and Broadband Acoustic Scattering from Turbulent and Double-Diffusive Microstructure"**. It then was continued as a SW06 participation and analysis project entitled **"High-Frequency Broadband Acoustic Scattering from Non-Linear Internal Waves during SW06"**.

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ABSTRACT

The long-term goal of this research is to understand high-frequency broadband acoustic backscattering from small-scale physical processes, such as internal waves, turbulence, and microstructure, in shallow, stratified coastal waters.

The primary objective of the proposed research was to measure high-frequency broadband acoustic backscattering in highly stratified, energetic environments and to determine the contribution to scattering from temperature and salinity microstructure. Testing the validity of existing scattering models and the initial development of new, and/or extension of existing, simple physics-based scattering models was a secondary objective of this work.

To accomplish the stated objectives, high-frequency broadband (150-600 kHz) acoustic backscattering measurements were performed during the generation, propagation, and dissipation of non-linear internal waves in August 2006 as a part of the SW06/NLIWI experiment. Almost coincident microstructure measurements were collected by Jim Moum with a profiling microstructure instrument, Chameleon. The contribution to scattering from biological organisms was quantified using a multiple-opening and closing net and environmental sensing system (MOCNESS), from which the zooplankton taxa, size, and depth (in coarse vertical bins) can be determined.

BACKGROUND

Over the last 40 years, there has been significant research effort directed at using high-frequency acoustic scattering techniques to remotely investigate the distribution, abundance, and size of marine organisms (Simmonds and MacLennan, 2005, and references therein). In fact, some of the world's largest stocks of zooplankton, such as Antarctic Krill (Nicol and Endo, 1999), as well as large fish stocks, are assessed using single or multi-frequency narrowband acoustic scattering

techniques (Simmonds and MacLennan, 2005). More recently, there has also been significant effort directed towards the quantitative use of narrowband acoustic scattering techniques for investigating small-scale physical processes, such as oceanic microstructure (e.g. Goodman, 1990; Seim et al 1995; Lavery *et al.* 2003; Ross and Lueck, 2003; Warren et al, 2003). Acoustic scattering techniques provide a rapid, high-resolution, synoptic, remote sensing alternative to more traditional sampling strategies. Yet reducing the ambiguities in the quantitative interpretation of the acoustic returns, with the ultimate goal of accurate, remote classification and quantification of physical and/or biological scattering sources, remains one of the outstanding challenges.

In principle, measurements of high-frequency acoustic scattering from oceanic microstructure and zooplankton across a broad range of frequencies, spanning multiple octaves of bandwidth, can reduce the ambiguities typically associated to the interpretation of acoustic scattering at a single frequency or a limited number of discrete narrowband frequencies. The goal is to capitalize on the different characteristic frequency-dependent spectra associated to different scattering sources. The potential for this technique is supported by broadband measurements on caged aggregations of fish (e.g. Simmonds and Armstrong, 1990; Simmonds *et al.,* 1996), free-swimming individual fish (e.g. Lundgren and Nielsen, 2008), and numerous broadband laboratory measurements of fish (e.g. Reeder *et al,* 2003; Au and Benoit-Bird, 2008), squid (e.g. Lee *et al.*, 2009), zooplankton (e.g. Roberts and Jaffe, 2008), and different types of microstructure (e.g. Goodman and Oeschger, 2003; Lavery and Ross, 2007), as well as the fact that many toothed whales use broadband echolocation signals to detect and classify their prey (Au *et al.,* 1999).

There are only a few commercially available (Ross and Lawson, 2009: 85–155 kHz, slightly less than an octave bandwidth), or custom-built prototype (Foote *et al.*, 2005: 25 kHz to 3.2 MHz using seven octave bandwidth transducers), high-frequency broadband acoustic backscattering systems that have been used for studying zooplankton and/or microstructure in the field. In contrast, lower-frequency broadband acoustic scattering measurements (< 120 kHz) to remotely characterize fish have been performed more prevalently (e.g. Zakharia et al., 1996; Stanton *et al.* 2010), including measurements involving explosives (e.g. Holliday, 1972; Thompson and Love, 1996; Nero *et al.,* 1998; Love *et al.*, 2004).

The broadband system developed for this project was used to measure high-frequency broadband acoustic backscattering from microstructure and zooplankton in the presence of surface trapped nonlinear internal waves of depression propagating over the New Jersey continental shelf. The frequency range used in this study encompasses many of the narrowband acoustic frequencies typically used to survey zooplankton and turbulent oceanic microstructure, and includes the Rayleigh-to-geometric scattering transition of some typical zooplankton and the diffusive roll-off in the spectrum for scattering from turbulent temperature microstructure for a range of dissipation rates. Almost coincident direct microstructure measurements were performed. Zooplankton community structure was characterized using depth-resolved net-sampling techniques. Some marine organisms, predominantly small fish and zooplankton, can act as passive tracers of physical processes such as internal waves and turbulence, and are a significant confounding factor during the interpretation of high-frequency acoustic volume backscattering. The combination of these data is necessary for the accurate interpretation of the acoustic scattering measurements and, in particular, to determine the relative contribution to scattering from zooplankton and turbulent

microstructure. Surface trapped nonlinear internal solitary waves of depression are a unique feature of coastal oceans and provide a good environment to assess the contribution to scattering from oceanic microstructure as they are both intensely turbulent (Moum *et al.,* 2003) and at sufficiently close range that they generate high signal levels well within the range of surface-deployed, high-frequency broadband acoustic scattering systems. Surface trapped nonlinear internal waves of depression are thought to be generated in the vicinity of the continental shelf break due to the interaction of internal tides with stratified fluid over sharp topography. They then propagate across the continental shelf until they dissipate in shallower waters. Not all the internal wave energy is dissipated in shallow waters, as some is dissipated by the generation of turbulence along the propagation path. Mechanisms for this dissipation of energy are discussed by Moum *et al.* (2003). It is hoped that quantification of broadband acoustic scattering from microstructure generated by these nonlinear internal waves may contribute to understanding these dissipation mechanisms.

The data analysis involved capitalizing on the broadband nature of the transmitted signals and using pulse compression techniques (Chu and Stanton, 1998; Stanton and Chu, 2008) to both increase the signal-to-noise ratio and the spatial resolution of the measurements. It has been possible to obtain order cm scale resolution in the direction of acoustic propagation using these techniques, a significant improvement over traditional single-frequency echosounder observations of water-column volume scattering. Additional information is obtained by further capitalizing on the broadband nature of the acoustic signals by using the spectral content of the scattering to determine if the scattering is consistent with scattering from small-scale physical processes or biology. In regions in which the scattering is determined to be dominated by turbulent microstructure, scattering models have been used to extract parameters such as the dissipation rate of turbulent kinetic energy. In regions in which the scattering is determined to be dominated by small zooplankton, scattering models have been used to infer parameters such as size and abundance.

WORK COMPLETED

Instrument development and calibration: A 4-channel high-frequency broadband acoustic backscattering system has been developed spanning the frequency range, in four almost overlapping bins, from 150 kHz to 590 kHz with similar acoustic scattering volumes. The system is designed to either profile with the transducers in a side-looking mode or to be suspended at a particular depth with down-looking transducers (resembling a more traditional echosounder). A SeaBird SBE 49 FastCAT CTD (16 Hz sampling rate) is mounted on the system to measure fine-scale temperature and salinity gradients while in profiling mode. Pitch, roll, and heading are also measured. GPS data are recorded to allow accurate synchronization with other instruments. The system has been calibrated, including measurements of beam patterns, in sea-water tanks at WHOI and at SMAST (on multiple occasions), in the WHOI sea well (also on multiple occasions), and in-situ, using 20 mm and 38.01 mm diameter Tungsten Carbide standard targets

Field measurements: This system has been deployed during the SW06/NLIWI experiment during a month long cruise (July 30- August28, 2006) on the RV Oceanus. Direct microstructure measurements were performed by Jim Moum using the turbulence profiler Chameleon (Moum et

al., 1995). The broadband acoustic system was fully operational throughout the experiment and high-frequency broadband acoustic backscattering has been measured for 28 internal solitary wave trains, in some cases chased over many kilometers from generation to dissipation stages. The acoustic system was deployed in both down-looking and side-looking mode, allowing scattering anisotropy during the passage of internal solitary waves to be investigated. In addition, 5 depth-resolved net tows (MOCNESS) were performed during this experiment in order to quantify biological scatterers.

Analysis of microstructure and biological measurements: Jim Moum is primarily responsible for the analysis of the microstructure measurements, and much of the data collected during the field experiment has been analyzed. These data have been used with existing scattering models (Lavery et al., 2003) to predict scattering from microstructure, and to assess the importance of salinity versus temperature microstructure. These data helped guide the locations for which intensive acoustic analysis was performed. All the shelf-break MOCNESS tows (2-5) have been analyzed for composition, size, and abundance of zooplankton. Predictions of scattering from zooplankton based on existing scattering models (Lavery et al., 2007) have been performed for these tows (the "forward problem") to determine the contribution to scattering from biology and to determine the dominant biological scatterers.

Analysis of acoustic scattering data: The analysis of the broadband acoustic scattering data has focused on locations at which particularly strong temperature gradients and high dissipation rates were observed, such as Kelvin-Helmholtz shear instabilities (Moum *et al.,* 2003). Elevated scattering from microstructure relative to zooplankton is expected at these locations. Two papers have resulted from this recent work (Lavery et al., 2010a, 2010b).

Turbulence anisotropy: Doris Leong, a recently graduated M.Sc. student at Dalhousie University has used the broadband acoustic scattering spectra measured during the SW06/NLIWI experiment to assess the importance of turbulence anisotropy (Leong, 2009). A manuscript will be submitted to the J. Acoustic. Soc. Am. on the data analysis.

RESULTS

High-resolution imaging of small-scale physical processes: Broadband acoustic scattering measurements enable the use pulse compression signal processing techniques to obtain very high resolution images of many nonlinear internal waves. In combination with the high ping rate (1 Hz), these techniques have allowed fine scale physical processes, such as Kelvin-Helmholtz shear instabilities (Fig. 1), typically not well resolved by the direct microstructure measurements, to be imaged at very high resolution. Though the direct microstructure measurements provide very high resolution measurements in the vertical, the profiles are relatively sparse (one profile every 2-4 minutes) relative to the acoustic measurements or the spatial scales of the KH instabilities.

Analysis of biological samples and the forward problem based on these data: All the MOCENSS tows performed on the continental shelf during the SW06 experiment have been analyzed (MOCs 2-5). The results show that, in general, biomass and numerical abundance of zooplankton are dominated by copepods, with larger copepods located in a deep scattering layer and the shallower

waters being populated by smaller copepods. All tows were performed during day light hours. Scattering predictions based on these data and available zooplankton models (Lavery et al., 2007) have shown that the predicted scattering from zooplankton is dominated by copepods, amphipods, and pteropods, depending on the frequency, depth, and location.

Forward problem based on microstructure data: Scattering predictions have also been made based on the microstructure data and turbulent microstructure scattering models, at select locations. These predictions suggest that the scattering from microstructure is dominated by temperature and not salinity microstructure, as would be expected based on the temperature and salinity gradients.

Scattering due to small-scale physical processes versus biology: Though the frequency response of the scattering was often consistent with scattering from small zooplankton (scattering increasing with increasing frequency: Fig. 2), some regions have been found in which the scattered frequency spectra are indicative of scattering from physical processes (Fig. 2). Specifically, scattering spectra from Kelvin-Helmholtz shear instabilities were frequently consistent with scattering from microstructure alone (scattering decreases with increasing frequency: Fig. 3).

Inversion of broadband data for biological and physical parameters: Simple least squares inversions of the broadband scattering data have been performed at locations in which the scattering spectra are consistent with scattering from small zooplankton alone, and consistent with scattering from microstructure alone. These inversions rely heavily on existing scattering models. For zooplankton, a single scattering type is assumed and the inversions result in size and abundance of that type of scatterer. For microstructure, the inversions allow the dissipation rate of turbulent kinetic energy (Fig. 4) and temperature variance (Fig. 5) to be deduced. For both these types of inversions the results are consistent with the direct sampling techniques, though high noise levels on the two highest frequency channels only allowed high values of dissipation rates of turbulent kinetic energy to be inferred.

Scattering anisotropy: By comparing broadband acoustic scattering spectra measured in horizontal and vertical mode, it has been possible to assess the importance of anisotropy on scattering. The overall scattering shows statistical patterns in spectral shape that suggests anisotropy occurs in either the biology or microstructure, though there was insufficient bandwidth and/or groundtruthing to determine which. However, turbulence dissipation rates inferred from acoustic inversions of spectra yield no clear evidence of small-scale turbulence anisotropy.

RECENT PUBLICATIONS RELATED TO THIS PROJECT

Lavery, A.C., Chu, D., and Moum, J. 2010a. Discrimination of scattering from zooplankton and oceanic microstructure using a broadband echosounder. *ICES Journal of Marine Science* **67**(2), 379-394.

Lavery, A.C., Chu, D., and Moum, J. 2010b. Observations of broadband acoustic backscattering from nonlinear internal waves: Assessing the contributions from microstructure. IEEE *Journal of Oceanic Engineering (in press).*

FIGURES

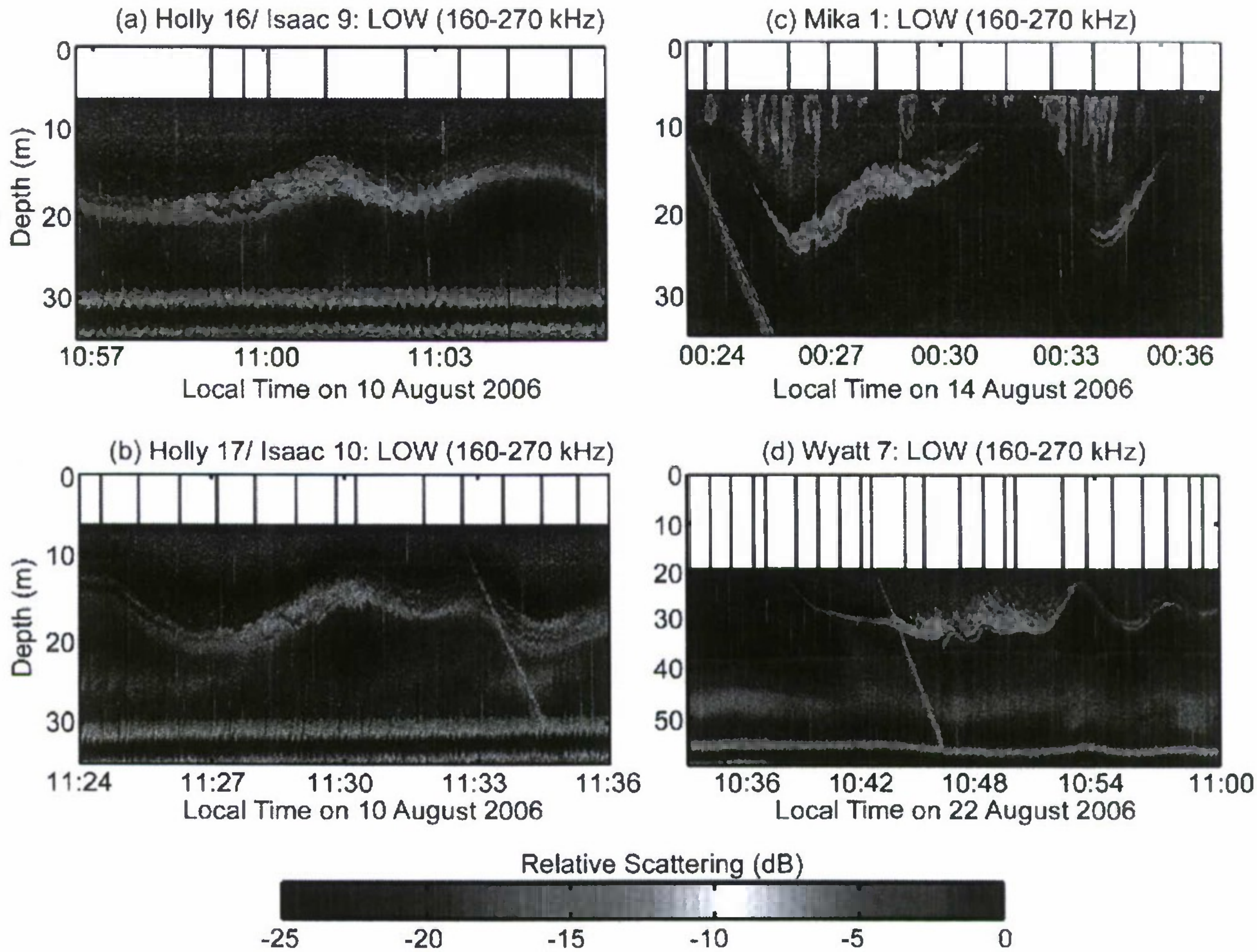

Figure 1: Compressed pulse output for the LOW (160-270 kHz) frequency channel during the passage of four non-linear internal waves illustrating high-resolution images of scattering from Kelvin-Helmholtz shear instabilities. The vertical lines at the top of each panel denote the times of the direct microstructure profiles. All images in this report have the same color bar scale.

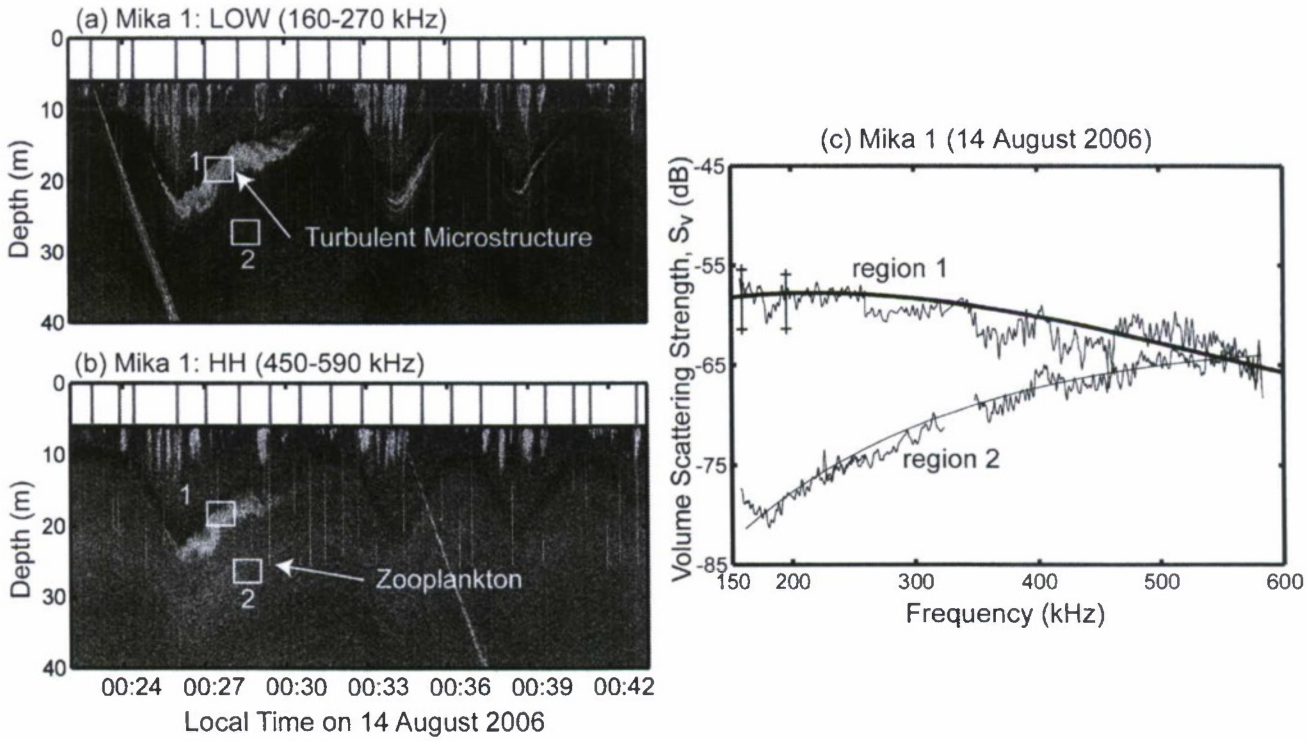

Figure 2: Compressed pulse output for the (a) LOW (160-270 kHz) and (b) HH (450-590 kHz) frequency channels during the passage of nonlinear internal wave Mika. The scattering spectra (c) associated to the KH shear instability (region 1) are generally consistent with scattering from microstructure, while the spectra associated to the deeper more diffuse scattering layer (region2) are consistent with scattering from small zooplankton.

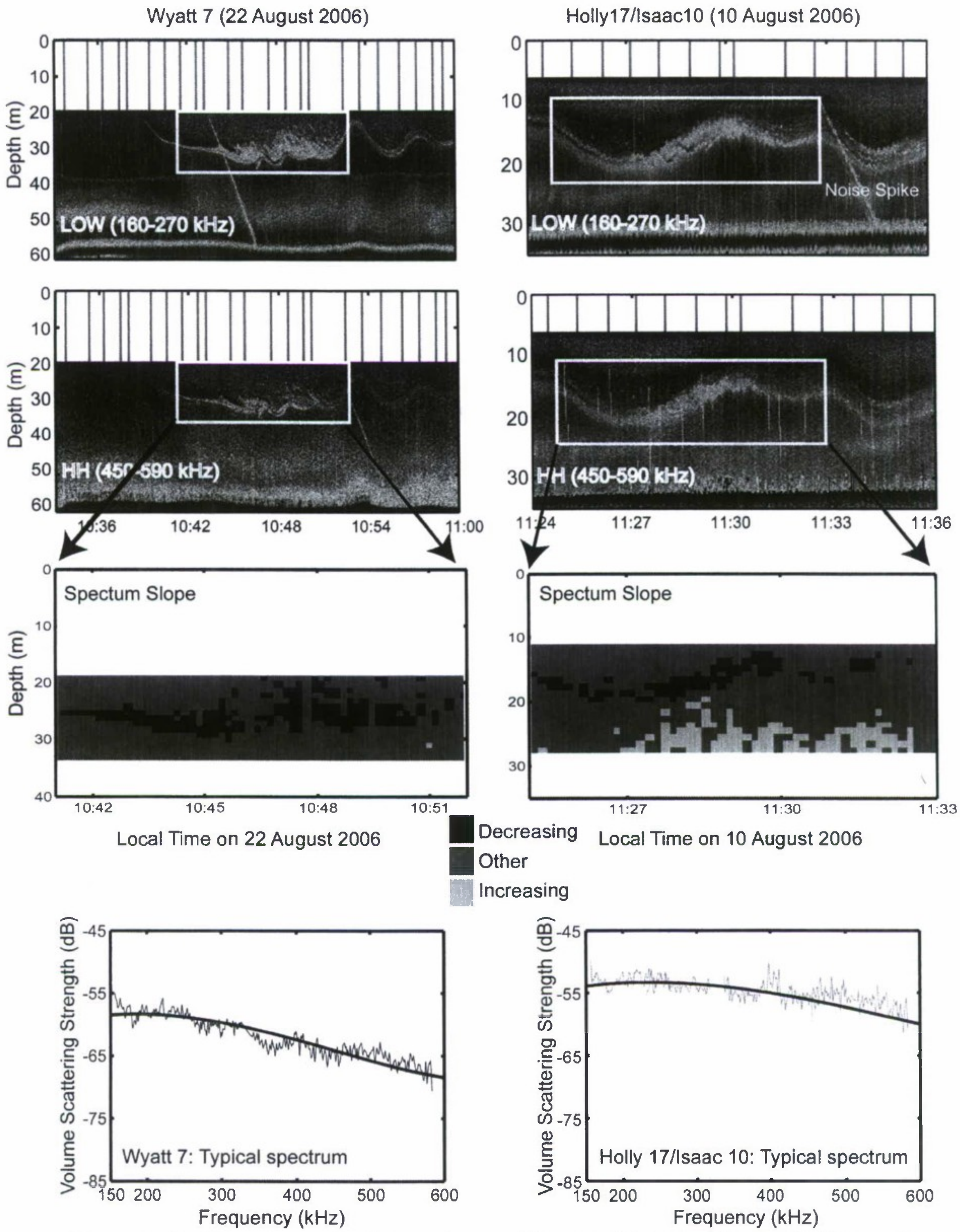

Figure 3: Left hand panels: Internal wave Wyatt 7. Right hand panels: Internal wave Holly17/Isaac 10. Top panels: Compressed pulse output for the LOW (160-270 kHz) frequency channel. Second row: Compressed pulse output for the HH (450-590 kHz) frequency channel. Third row: Slope analysis for the measured spectra. Final row: Typical spectra associated to the KH shear instabilities.

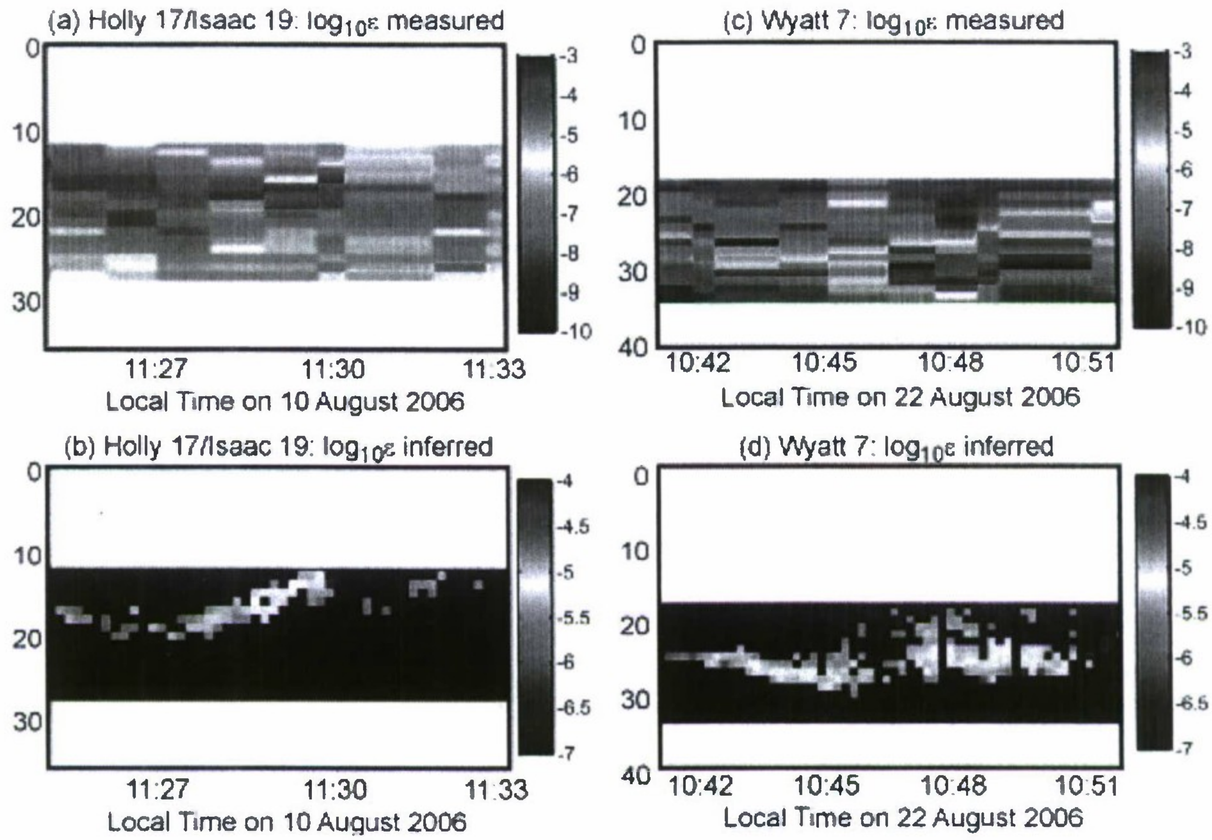

Figure 4: Comparison of the directly measured and acoustically inferred dissipation rates of turbulent kinetic energy for nonlinear internal wave Holly 17/Isaac 10 (a and b), and for nonlinear internal wave Wyatt 7 (c and d).

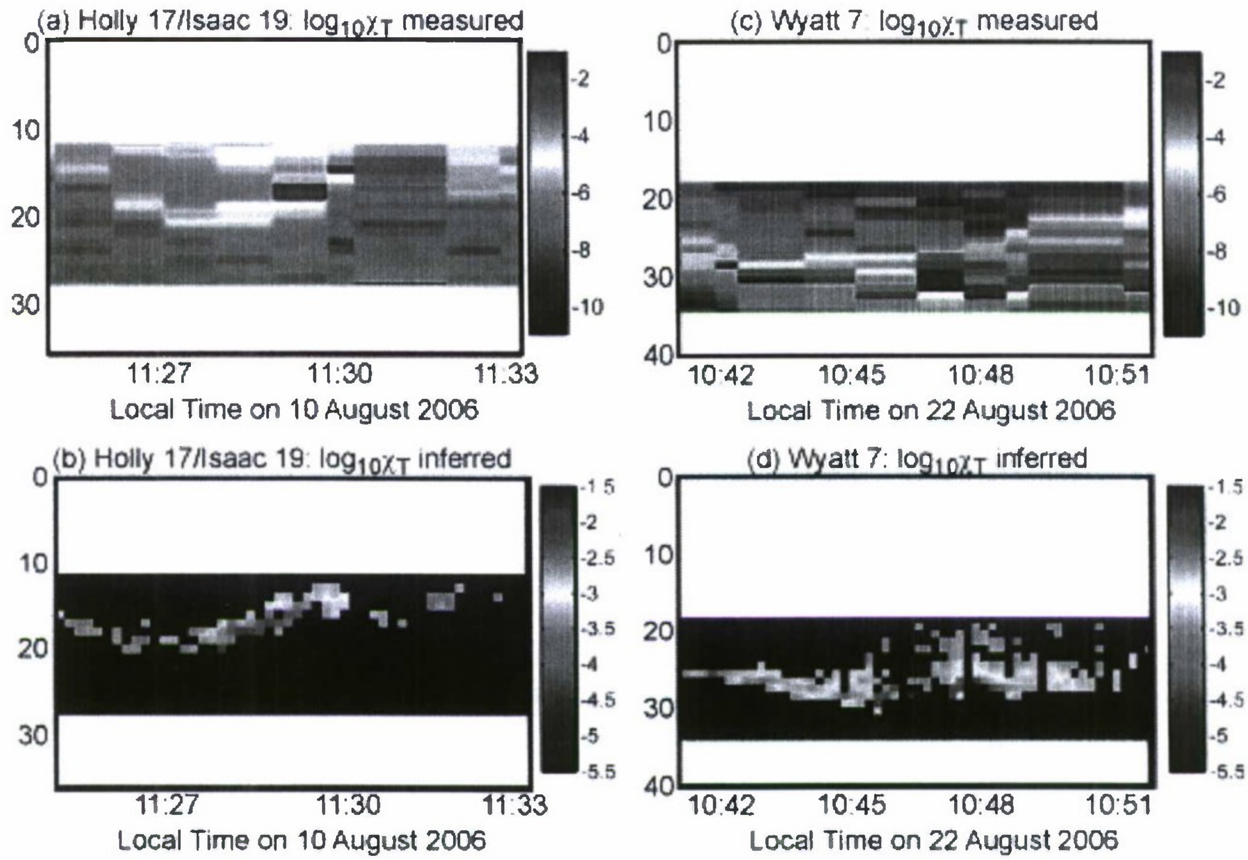

Figure 5: Comparison of the directly measured and acoustically inferred dissipation rates of temperature variance for nonlinear internal wave Holly 17/Isaac 10 (a and b), and for nonlinear internal wave Wyatt 7 (c and d).

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